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A FEASIBILITY STUDY ON THE MEASUREMENT
OF THE TIME-DEPENDENT
SHROUD PRESSURE OF A DUCTED PROPELLER

by

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ABSTRACT

Results of a limited study on the measurement of the instantaneous incremental shroud pressure on a ducted propeller by means of a piezoelectric transducer are given. The instrumentation is described and photographs of the observed pressure pattern presented. The feasibility of such measurements, the reproducibility and quality of the signal, and the magnitude and decay of the higher harmonics over a range of advance ratios are examined. Recommendations for future tests are outlined.

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NOMENCLATURE

$f_1, f_2, \ldots$	blade harmonic frequency, Ω/π, $2\Omega/\pi$, ..., cps
J	propeller advance ratio, $U/\Omega R_p$
p	static pressure, lb/ft^2
Δp	incremental shroud static pressure, lb/ft^2
q	dynamic pressure, lb/ft^2
R_p	propeller radius, ft
U	tunnel test section velocity, ft/sec
Ω	propeller angular velocity, rad/sec

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INTRODUCTION

Over the past two and a half years a three-dimensional theory[1] for a finite-bladed ducted propeller operating in axial flow has been developed. Primary emphasis[2,3] has been placed upon the mean, or zeroth harmonic, solution, but this does not mean that the higher harmonics are unimportant. They could play an influential role in the study of the problems of noise generation, structural vibration, and possible unsteady boundary layer phenomena. Accordingly, it is felt that appropriate experiments can provide valuable insight as to possible predominant behavior of certain harmonics in addition to estimates of the magnitude of their effects.

This report contains the results of a preliminary study on the measurement of the time-dependent shroud pressure. Prior to the present test, a detailed literature search revealed that no previous studies of the time-dependent shroud pressure on ducted propellers had been undertaken although several investigators have measured the chordwise variation in static pressure on the shroud[4-7]. The time-dependent pressure field of a free propeller has received somewhat more attention[8-15], principally from hydrodynamicists.

Very little was known a priori regarding preferable instrumentation to be used to record the incremental pressure pattern. The basic limitation imposed upon the pressure transducer was one of size. The transducer and output lead had to be mounted completely in the shroud of the test model, the maximum length available being approximately 1 - 1¼ in. for typical maximum shroud model thicknesses. In addition, the transducer had to have a linear response up to several kilocycles and a high signal sensitivity in the low pressure range. A thorough study of available pressure gauges was made and it was decided that one with a piezoelectric sensing element best fulfilled these requirements.

The specific items to be studied were: (i) feasibility of recording the time-dependent shroud pressures with a piezoelectric gauge, (ii) if feasible, the reproducibility and quality of the data, and (iii) qualitative measurement of the magnitude and decay of the harmonic content. Chapter One contains a description of the test facilities, ducted propeller model, instrumentation, and test procedure. Chapter Two presents the test results in the form of photographs of the observed pressure patterns. Data reproducibility and quality are investigated and the results of the harmonic analysis presented. In addition, the presence of spurious signals is examined briefly. Finally, conclusions and recommendations for future measurements are given.

CHAPTER ONE

TEST PREPARATIONS

1.1 General Considerations

As previously stated, the primary purpose of this test was the determination of data recording and interpretation problems associated with the particular instrumentation selected to measure the time-dependent shroud pressure. On this basis, the use of a readily available test model was dictated and the variation of aerodynamic and geometric parameters kept to a minimum.

1.2 Facilities

The tests were carried out in the south wind tunnel of the Subsonic Aerodynamics Laboratory of the David Taylor Model Basin. The test section of this tunnel is 8 ft by 10 ft in cross section and 14 ft long. Further details regarding the test facilities may be found in Ref. 16.

1.3 Model

The model employed was a modified version of the Hiller Aircraft high-speed configuration D_1P_2S which had been used in previous ducted propeller experimental investigations[17]. The Hiller model originally was equipped with contra-rotating propellers; however, the rear propeller was removed for this test in order to provide a closer correlation between the test and theoretical model. The test model, mounted in the wind tunnel, is shown in Fig. 1.1. The geometry for the shroud is given in Table 1.1, and that for the propeller in Table 1.2.

The model was powered by a variable-frequency, water-cooled electric motor rated at 75 hp at 12,000 rpm. The support system is shown in Fig. 1.1. The shroud inner surface at the propeller plane was painted with a conducting paint to detect any evidence of propeller-shroud fouling for shut-down.

1.4 Instrumentation

The time-dependent pressure was measured by an Atlantic Research Corporation Model LC-60 piezoelectric transducer. The sensing element, a lead zirconate crystal, is relatively temperature insensitive, has a high output sensitivity and a linear frequency response up to several kilocycles. The transducer, see Fig. 1.2, is 0.50 in. in diameter and 0.58 in. long and was located at the 30% chord position at the top of the shroud.

The transducer output was fed through approximately 34 ft of Microdot "Mininoise" cable to a decade preamplifier which increased the signal level by a factor of 10. The preamplifier output was fed to channel B of a dual channel oscilloscope and the trace photographed. Actually, several

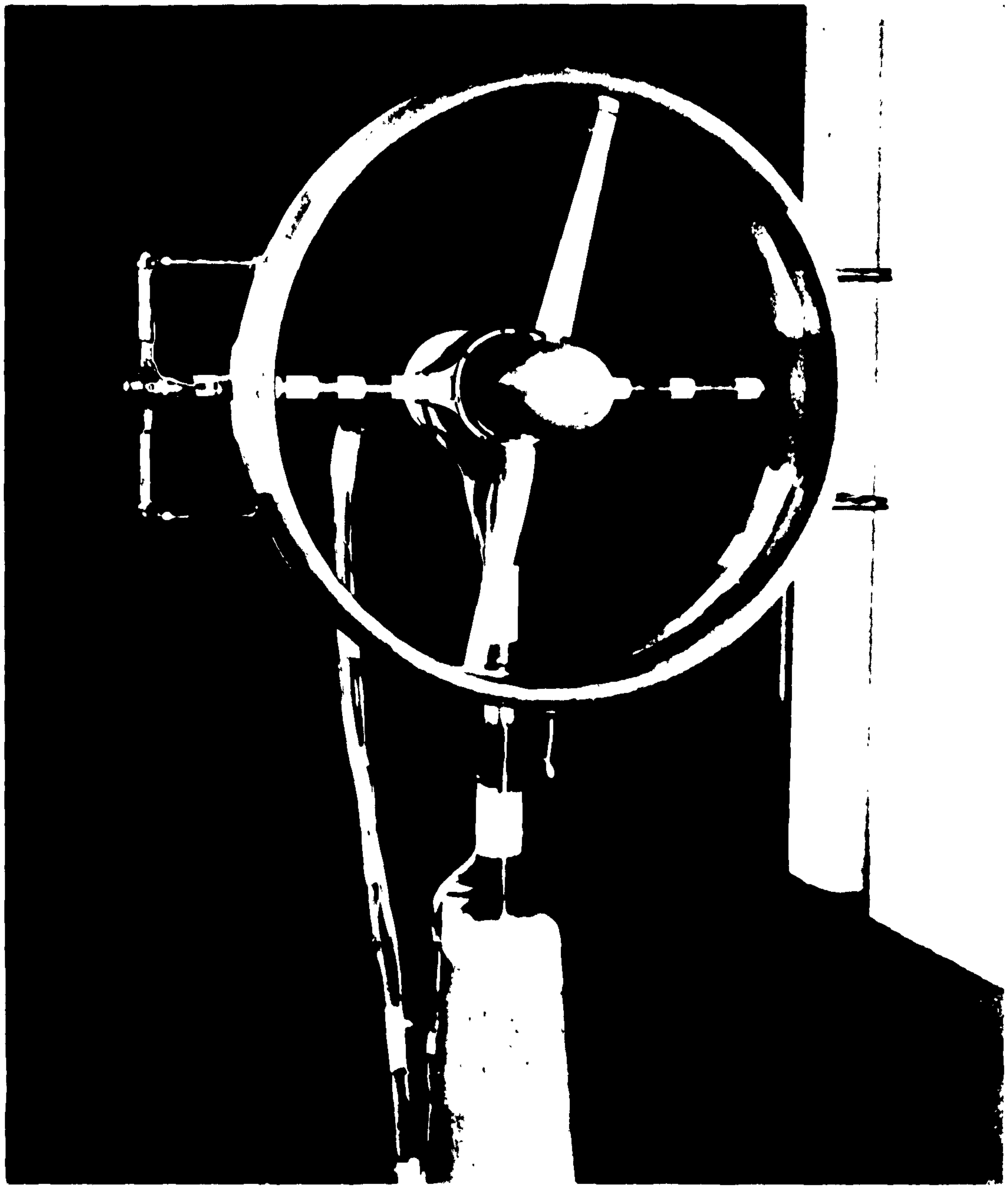

FIGURE 1.1

TEST MODEL

MODIFIED HILLER CONFIGURATION D_1P_2S

TABLE 1.1

SHROUD SECTIONAL GEOMETRY

Chord, in.	Ordinate, in. Upper	Ordinate, in. Lower
0	0	0
0.15	0.396	-0.182
0.30	0.518	-0.250
0.60	0.692	-0.311
0.90	0.806	-0.331
1.20	0.886	-0.329
1.80	0.970	-0.293
2.40	0.970	-0.251
3.00	0.910	-0.209
3.60	0.806	-0.167
4.20	0.664	-0.126
4.80	0.485	-0.084
5.40	0.272	-0.021
6.00	0	0

Section .... Modified NACA 6421

Inner Radius at Propeller Plane .... 1.001 ft

Maximum Thickness .... 1.263 in. at 30% Chord

Incidence of Chordline .... 4°
to Propeller Axis

TABLE 1.2

PROPELLER GEOMETRY

Station, $\%R_p$	Chord, in.	Twist, °
20	1.54	35.4
30	1.46	21.2
40	1.37	14.1
50	1.29	9.9
60	1.20	7.1
70	1.11	5.0
80	1.03	3.5
90	0.94	2.3
100	0.86	1.4

Section .... RAF-6 of 12% Thickness Ratio

Tip Radius .... 0.997 ft

Hub Diameter .... 0.333 ft

Propeller Plane .... 60.5% Shroud Chord

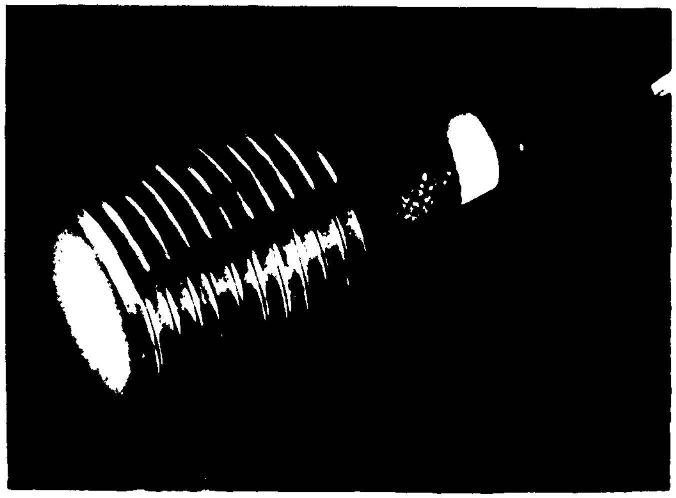

FIGURE 1.2

PIEZOELECTRIC PRESSURE TRANSDUCER

traces were superimposed in each photograph because facilities were unavailable to record a single trace. Voltage sensitivity of the transducer calibrated over the range 0 - 1.0 psi was linear at 0.091 volts/psi at the oscilloscope.

The local static pressure at the same chordwise station and diametrically opposite from the pressure transducer was measured in conventional fashion; the orifice and connecting tube can be seen at the bottom of the shroud in Fig. 1.1.

A small Miniatron impulse generator was fitted in the shroud at the propeller plane, 90.2° from the transducer, to determine the instantaneous angular position of the propeller relative to the pressure transducer. A very fine coating of iron filings glued to the blade tips activated the generator with each blade passage. The output was fed to channel A of the oscilloscope and simultaneously displayed with the instantaneous pressure signal.

The harmonic content of the time-dependent pressure signal was found by feeding the transducer output into a General Radio wave analyzer.

A schematic diagram of the instrumentation connections is depicted in Fig. 1.3.

1.5 Procedure

Pressure readings on both the inner and outer shroud surfaces were recorded over a range of advance ratio J , defined as the ratio of the tunnel test section velocity U to the propeller tip velocity ΩR_p , from 0.14 to 0.35 . The advance ratio was fixed by setting the wind tunnel dynamic pressure q at a prearranged value and then adjusting the propeller angular velocity Ω to give the desired J . Several runs at identical advance ratios were carried out at different times of the same day and again on different days in order to ascertain the reproducibility of the data. One series of measurements was taken at constant Ω with varying q ; another at constant q with varying Ω . The test Reynolds number, based on the shroud chord, varied from 0.2×10^6 to 0.4×10^6 .

A check was made to determine the magnitude of any spurious signal. The transducer was sealed off from the

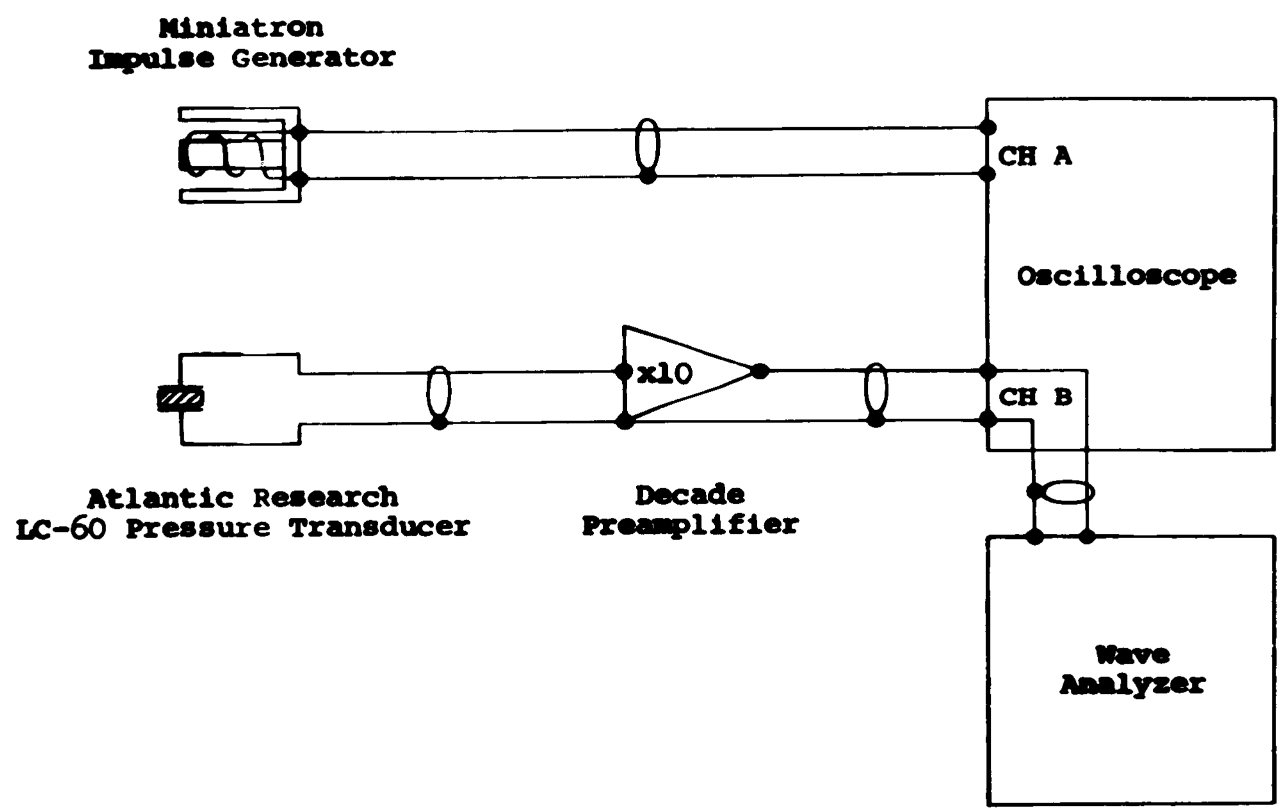

FIGURE 1.3

SCHEMATIC DIAGRAM OF INSTRUMENTATION CONNECTIONS

flow field by means of a metal disc and the resultant output was measured at identical running conditions.

CHAPTER TWO

RESULTS OF THE TESTS

2.1 General Considerations

The presentation of the main points is best illustrated by several typical examples; consequently, the complete details of individual runs are not given. As noted previously, the advance ratio was the only parameter changed.

2.2 Feasibility

The first objective of the test was to establish the feasibility of recording the time-dependent shroud pressure using a piezoelectric transducer. Photographs of the incremental pressure Δp on the shroud inner surface taken at different times are shown in Fig. 2.1 for an advance ratio of 0.20 and in Fig. 2.2 for an advance ratio of 0.31. The photographs on the left show approximately one complete period of the pressure signal. Those on the right have the time scale magnified five times. The reference signal is indicated by the lower trace in each figure and the propeller position is marked appropriately.

The frequency response of the transducer is satisfactory for the purposes of the experiment; that is, it follows the fluctuating signal well. In addition, the sensitivity of

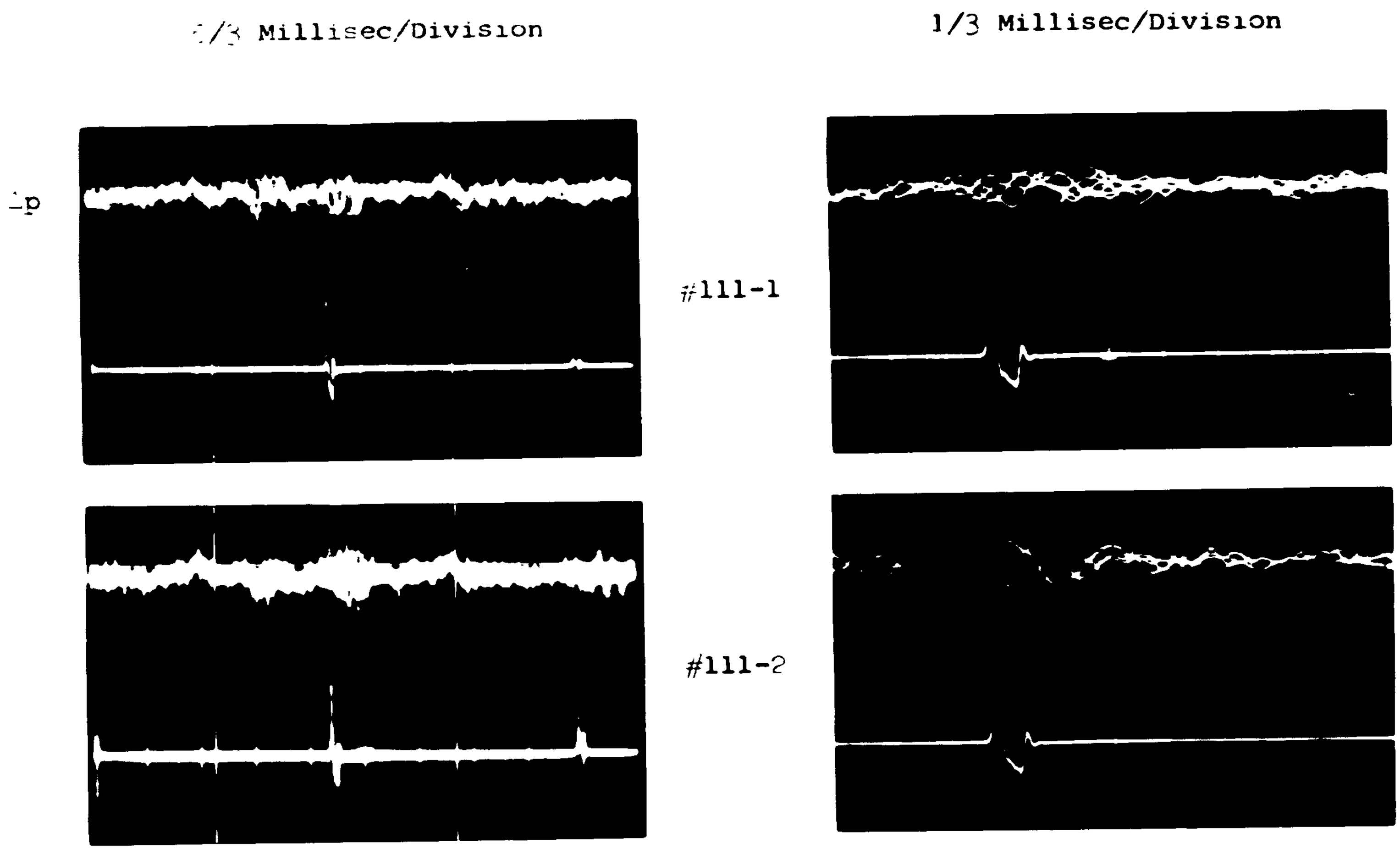

FIGURE 2.1

INSTANTANEOUS INCREMENTAL PRESSURE PATTERN ON SHROUD INNER SURFACE

TRANSDUCER AT 30% SHROUD CHORD, J = 0.20, VERTICAL UNIT: 15.7 LB/FT^2

5/3 Millisec/Division　　　1/3 Millisec/Division

Δp

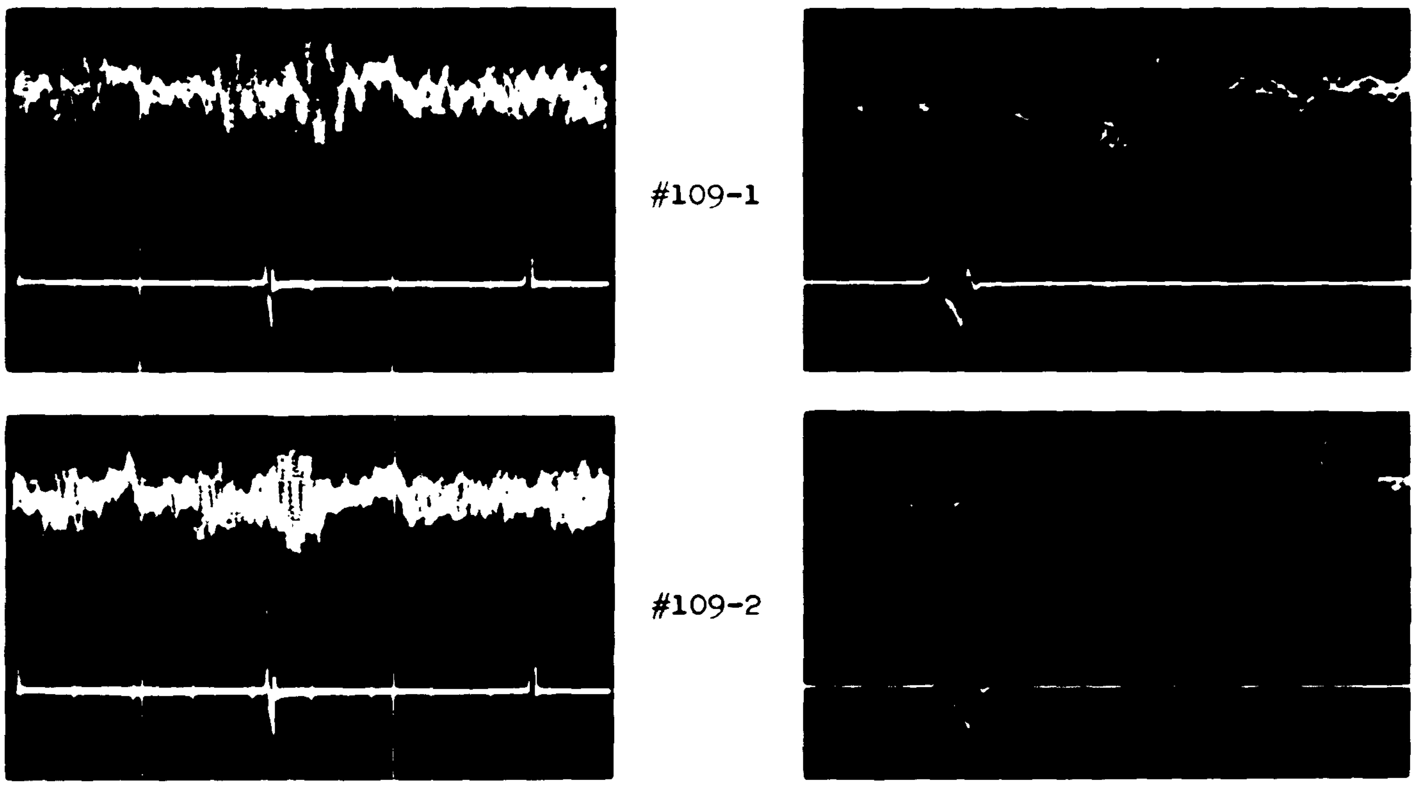

FIGURE 2.2

INSTANTANEOUS INCREMENTAL PRESSURE PATTERN ON SHROUD INNER SURFACE

TRANSDUCER AT 30% SHROUD CHORD, $J = 0.31$, VERTICAL UNIT: 15.7 LB/FT^2

the transducer-cable system is sufficient so that excessive preamplification of the input to the oscilloscope is not required to produce a readily recordable output. Examination of the records indicates that the propeller angular position relative to the center of the transducer can be determined to within $\pm\frac{1}{2}°$.

2.3 Reproducibility and Quality

At first glance the traces of Figs. 2.1 and 2.2 seem somewhat incoherent. Further examination, though, reveals that the more predominant features of the pressure signature for a given advance ratio were satisfactorily reproduced from trace to trace. For example, the maximum and minimum peak-to-peak signal magnitudes as seen from the photographs with the magnified time scale remain relatively consistent. Also, the basic frequency of the signal in many of the runs appears to be twice the rotational frequency as anticipated. Finally, there is a shift in the position of the relative signal maximums with respect to the transducer location for a change in propeller blade loading, see Fig. 2.3. As the propeller loading increases with increasing advance ratio, we see that the region of maximum incremental pressure moves towards the transducer location. This indicates a change in the relative magnitude of the sine and cosine components of any harmonic and/or a change in the frequency of the predominant harmonic.

J = 0.20 J = 0.31

FIGURE 2.3

SHIFT IN SIGNAL MAXIMUM WITH ADVANCE RATIO

Due to the fact that several traces, usually five or six, are superimposed upon one another, further interpretation of the data in the form shown is rather difficult. However, with the aid of an enlarged negative of the photographs, individual pressure patterns may be identified and redrawn. This was done for run #109-1 of Fig. 2.2 and the patterns fitted to each other approximately at the maximum and minimum signal points; the result is shown in Fig. 2.4. The quality of the signal now appears considerably better, and comparison with a trace taken some minutes later indicates good agreement. The principal discrepancy appears to be the phase difference between signatures. It varies in a seemingly random manner from one to nine degrees, or a time equivalent of 0.2 - 1.9% of the time to travel one shroud chord length. Explanation of this difference is somewhat difficult.

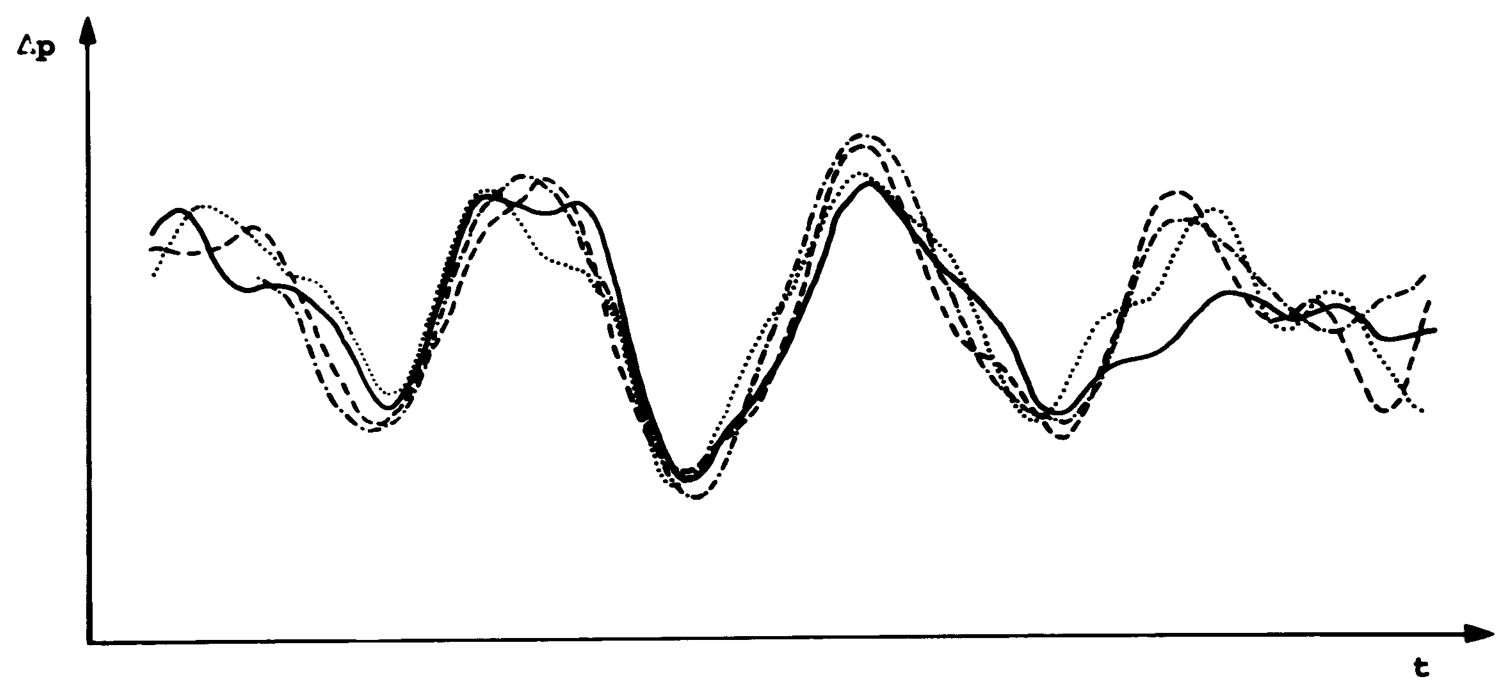

FIGURE 2.4

SUPERPOSITION OF TIME-DEPENDENT SHROUD PRESSURE PATTERNS

RUN #109-1, J = 0.31

Possibly it could be due to factors such as fluctuations in the tunnel velocity, variations from pure asymmetry in the shroud, or unsteady airfoil phenomena. It does not appear to be a triggering error since the reference signals are consistently superimposed.

Other minor deviations from the "average" signal pattern found in Fig. 2.4 suggest that some signal not solely due to aerodynamic pressure may be present. As indicated in Section 1.5, one series of test runs was made with the transducer blocked off from the passing air stream in order to detect any undesirable signal. The photographs taken under these conditions revealed a random signal having a nearly constant magnitude of approximately one-fourth of the maximum recorded by the transducer in its normal position at identical running conditions. This is believed to be due essentially to forces transmitted to the lead zirconate crystal through its mounting from the vibrating shroud. Unfortunately, the acceleration sensitivity characteristics of the transducer when vibrating both parallel and perpendicular to its axis are not known. It is true, however, that these transducers are quite sensitive[18] to accelerations, especially transverse ones.

In further tests of this nature, we would recommend that the acceleration sensitivity characteristics of the individual transducer be determined independently, as well as the instantaneous shroud acceleration during each test run by attaching an accelerometer at the transducer location. If the observed accelerations are larger than can be tolerated without introducing significant error, then the transducer should be shock insulated, say by some type of foam rubber mounting, or the shroud and propeller support systems decoupled.

2.4 Harmonic Analysis

From the traces shown in the figures and others taken in this series, the maximum amplitude incremental pressure appears to be of the same order of magnitude as the dynamic pressure based on the tunnel test section velocity; for example, at $J = 0.31$, $q \approx 20\ \mathrm{lb/ft^2}$ and $\Delta p \approx 15\ \mathrm{lb/ft^2}$. During a large part of the period the pressure fluctuation would of course be somewhat less than this and limited measurements indicate that the time-dependent pressure on the outer surface is less than that on the inner surface. Regardless, the magnitude of these incremental pressures warrants careful consideration of the higher harmonics.

Some results of the harmonic analysis of the fluctuating pressure signal are given in Table 2.1. The scale reading of the first harmonic of the blade frequency f_1 or Ω/π has been arbitrarily normalized to unity with successive values of $f_2 = 2\Omega/\pi$, ... adjusted accordingly. In some cases the readings for a particular harmonic varied with time; here the range of readings is given. Perhaps this may be

TABLE 2.1

VARIATION IN HARMONIC CONTENT WITH ADVANCE RATIO J

		Scale Reading			
J	f_1, cps	f_1/f_1	f_2/f_1	f_3/f_1	f_4/f_1
0.15	123	1.00	1.6-2.6	0.62	0.50
0.20	132	1.00	1.0-1.4	0.59	0.48
0.31	135	1.00	1.22	0.94	0.73

correlated with the random signals associated with shroud vibrations.

No specific conclusions regarding the variation in harmonic content with advance ratio may be given. In contrast to tests on free propellers[11,12], the magnitude of the second harmonic is greater than the first and the subsequent decay of the following harmonics is not as rapid. Theoretical predictions and further measurements are needed to verify or disprove this preliminary observation.

CONCLUSIONS

The feasibility of using a piezoelectric transducer to record the time-dependent shroud pressure on a ducted propeller has been investigated. The results show that:

The technique for the determination of the instantaneous angular position of the propeller and the frequency response and sensitivity of the transducer are satisfactory.

The more predominant features of the pressure signal are reproducible, but the quality is somewhat impaired by a spurious signal of appreciable magnitude. This signal is believed to be due to accelerations transmitted to the transducer by the vibrating shroud.

The maximum amplitude of the incremental pressure is of the same order of magnitude as the dynamic pressure of the free stream. From preliminary measurements, the variation of the harmonic content does not parallel that measured in free propeller tests.

Further investigations should incorporate certain improvements in the system as suggested and should include more detailed analyses of the observed phenomena.

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